Experimental results from the Cadarache 1 MV test bed with SINGAP accelerators

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1. Introduction and objectives
2. The SINGAP test bed at Cadarache
3. Experimental results and comparisons with simulations
4. What's next
5. Conclusions

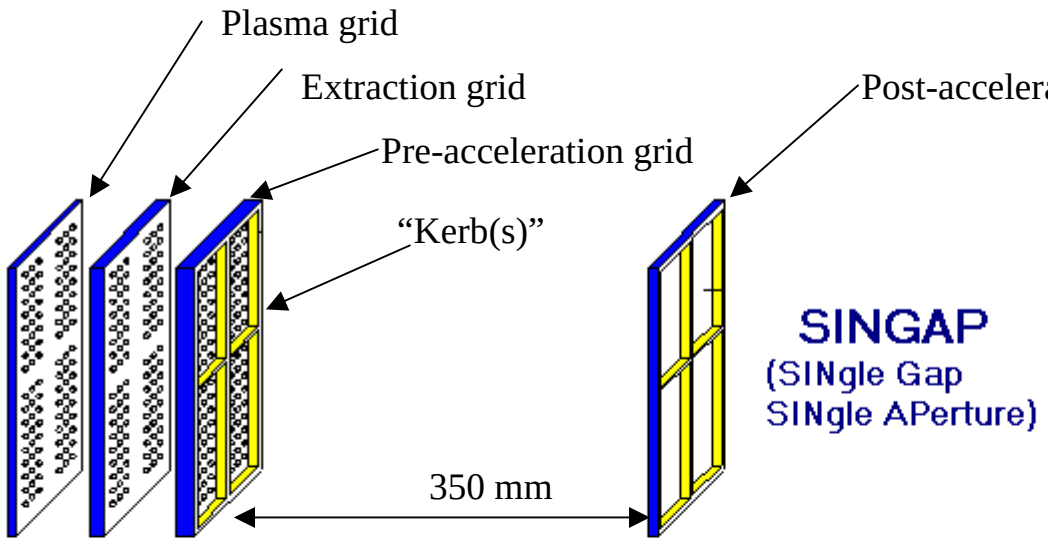
Introduction and objectives

- A prototype accelerator based on positive ion system was originally used to demonstrate the feasibility of a SINGAP accelerator
- With this accelerator we demonstrated that we could accelerate a D^- beam to 910 keV with a current density $J^- = 3$ mA / cm^2.
- The measured beam profiles on the target corresponded well with those predicted by calculations. However not with the quality required for ITER.
- In order to demonstrate ITER NBI (1MV, 40 A) relevant beam optics a new "ITER-like" accelerator has been put into operation at the Cadarache 1MV, 100 mA test bed.
- The "ITER-like" accelerator incorporates all the beam optics calculated to be necessary for the ITER SINGAP system.
- Present work under EFDA 5.1 B contract. The original contract period was from 19/12/2001 to 19/3/2004. It has been extended to June 2005.

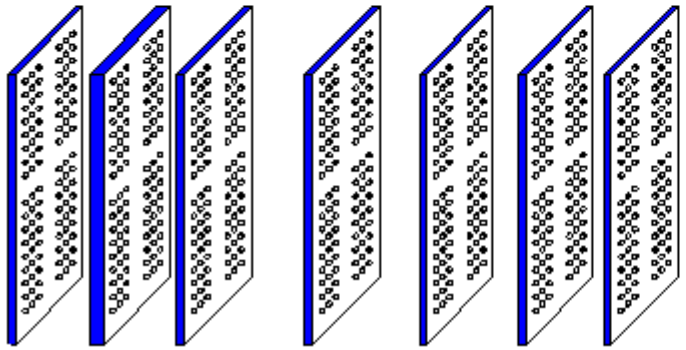
Introduction and objectives cont.

With the new ITER-like accelerator and ion source the objectives are to:

1. Demonstrate voltage holding with a main acceleration gap of 350 mm without and with gas from the ion source.
2. Produce H^- or D^- beams with acceptable beam-optics for ITER at energies close to 1 MeV (1 MeV and either 28 mA/cm^2 H^- or 20 mA/cm^2 D^- for pulse lengths ≥1 s).
3. Demonstrate the efficiency of the electron traps in a SINGAP accelerator.
4. Carry out test of the reliability of a SINGAP accelerator. Attempts will be made to fire a sequence of 50-100 pulses of up to 2 s length onto the beam dump with an energies close to 1 MeV.



SINGAP
(SINgle Gap
SINgle APerture)



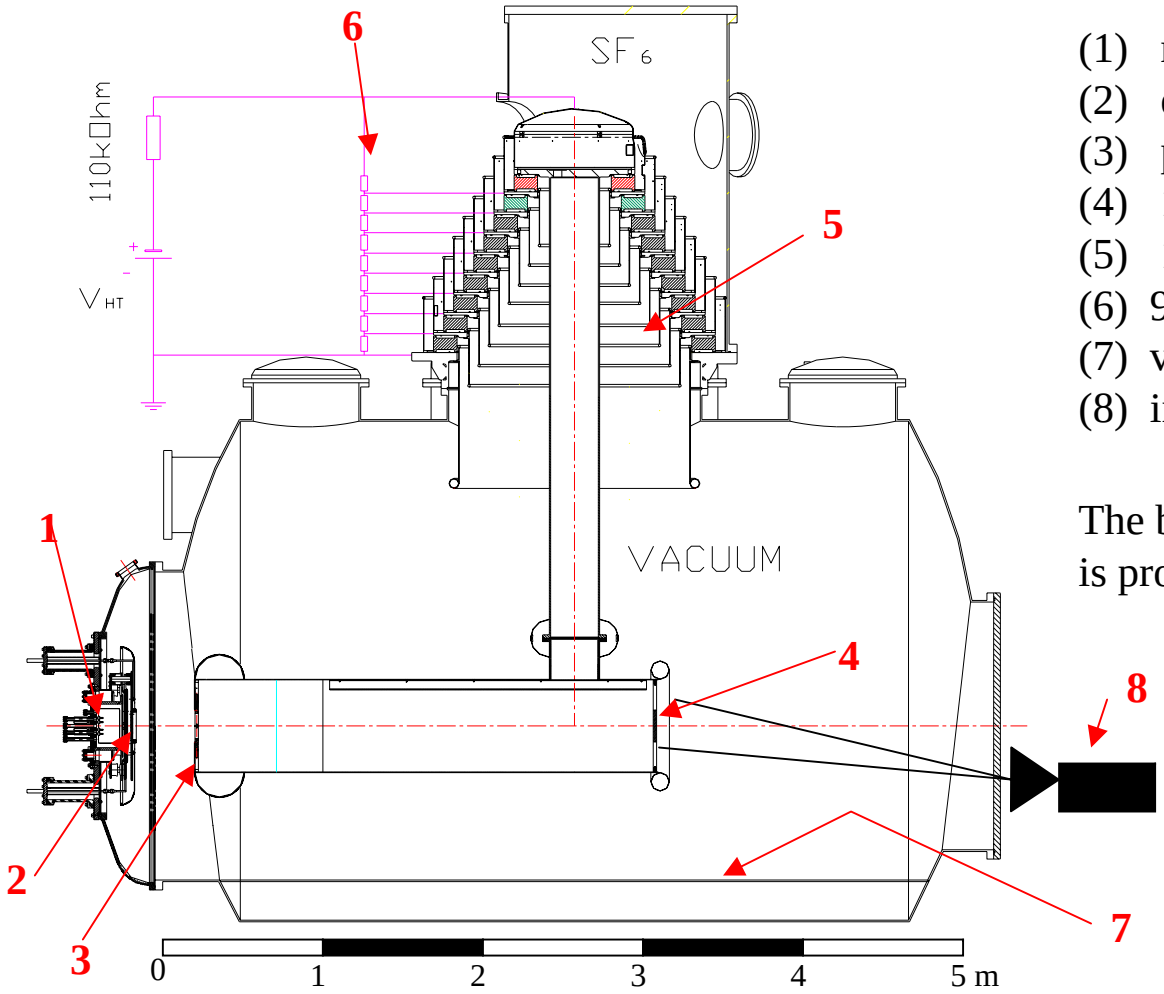
MAMuG
(Multi Aperture
Multi Grid)

ITER 1MV Accelerators

SINGAP
pre-accelerates beam to ~ 40 keV.
post-accelerates in a single step to 1 MeV.

MAMuG
accelerates extracted beam in 5 steps to 1 MeV.

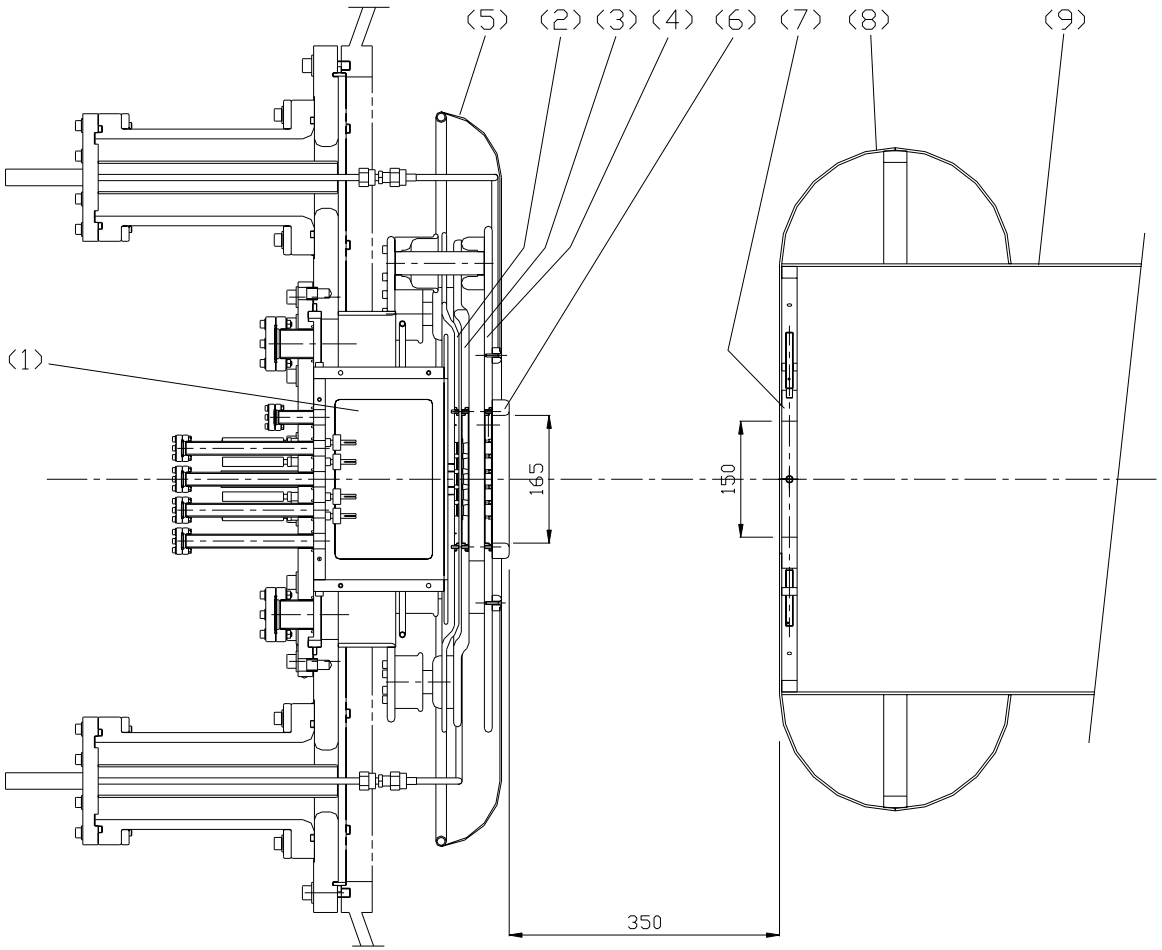
The 1 MV SINGAP test bed with the ITER-like accelerator



(1) negative ion source
(2) extractor / pre-accelerator
(3) post-accelerator (+1 MV)
(4) 1-D CFC graphite target
(5) 1 MV bushing
(6) 9x100 MΩ resistor chain
(7) vacuum vessel floor (0 V)
(8) infra-red camera

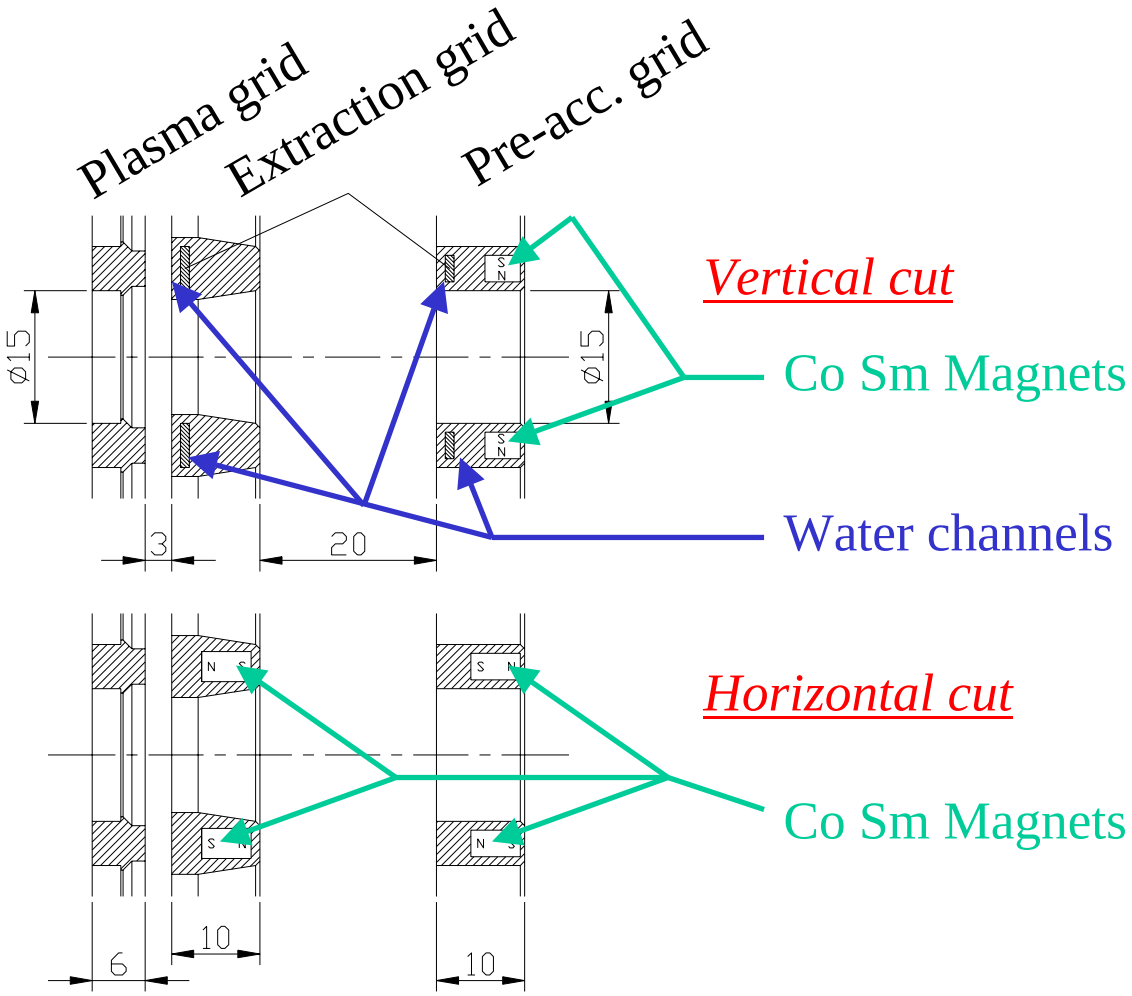
The background pressure of $<10^{-7}$mb is provided by a cryo sorption pump.

The “ITER-like” accelerator



(1) ’Drift Source’
(2) plasma grid support (~10 V)
(3) extraction grid support (<+10 kV)
(4) pre-acceleration grid support (<+50 kV)
(5) electrostatic screen
(6) electrostatic "kerb" structure
(7) post-accelerator electrode (+1 MV)
(8) electrostatic stress ring
(9) drift tube

The “ITER-like” accelerator



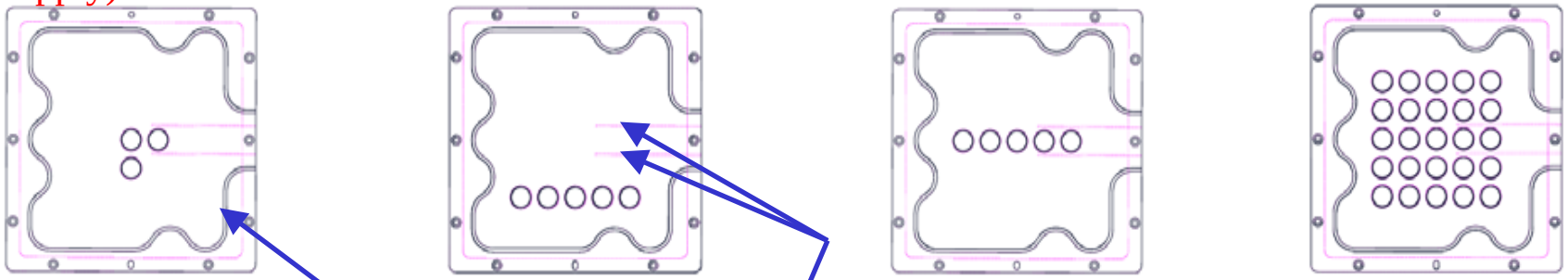
The “ITER-like” accelerator

Four different plasma grids are available for :

High J^- studies (with existing 1 MV 100 mA power supply)

Space charge and kerb effects

Higher current beams (≈ 1A) at JAERI

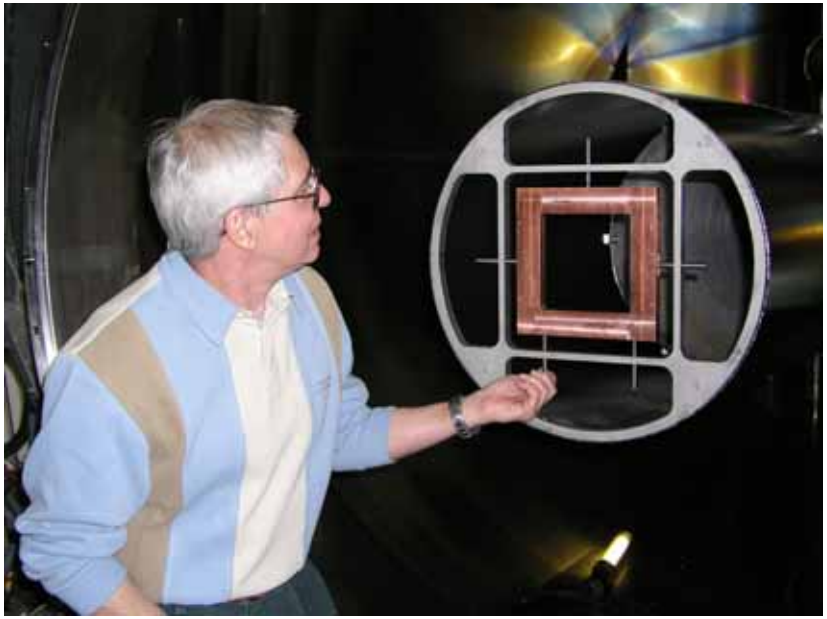


Thermocoax
Heating element

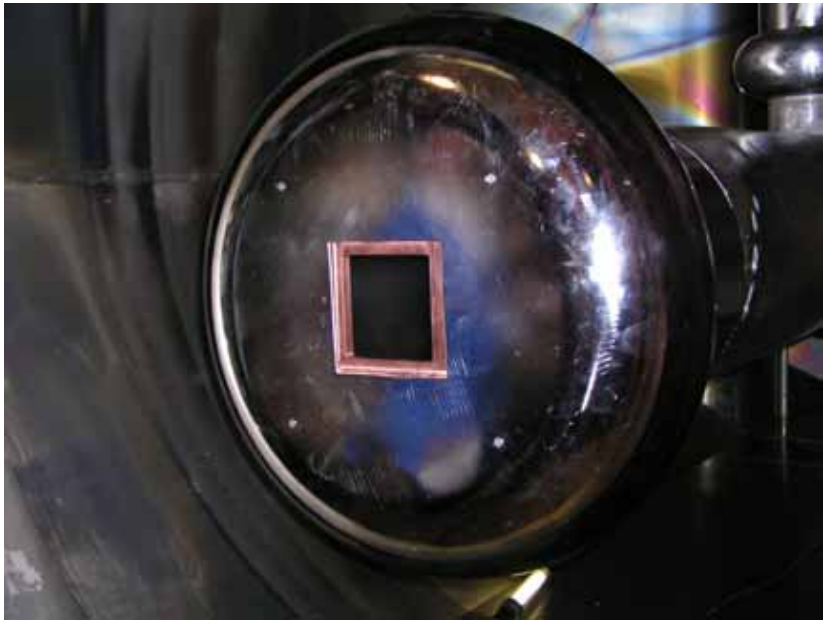
Thermocouples

The “ITER-like” accelerator

Post accelerator

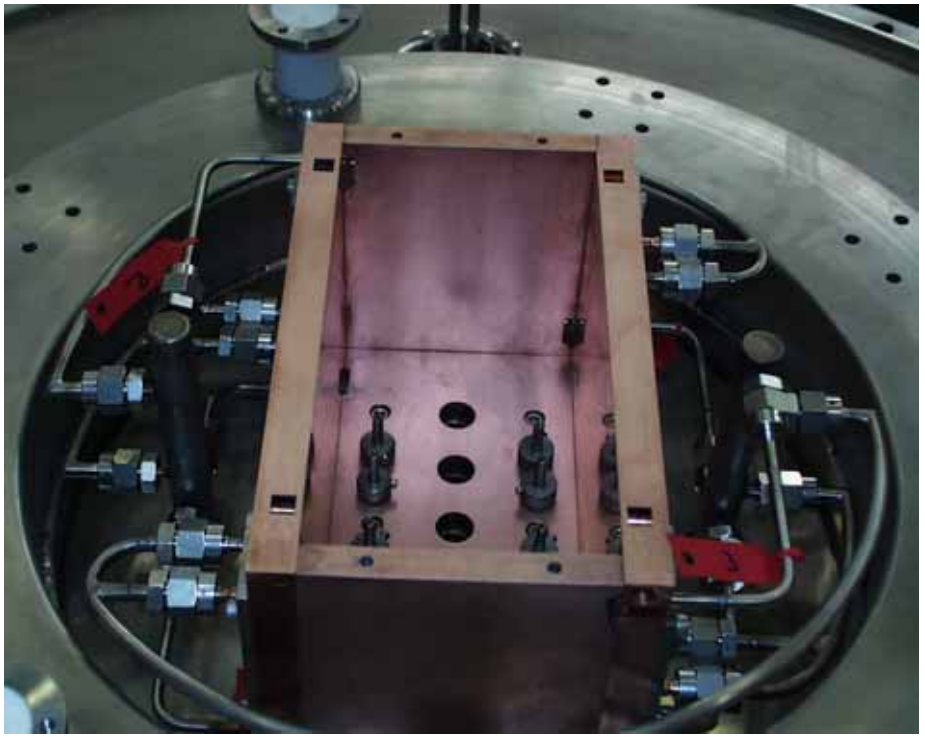


Movable post-accelerator electrode provides aperture offset steering to simulate the vertical steering (±0.55°) required on ITER or just for correction of misalignment.



Post acceleration electrode with electrostatic electrode.

The “ITER-like” accelerator



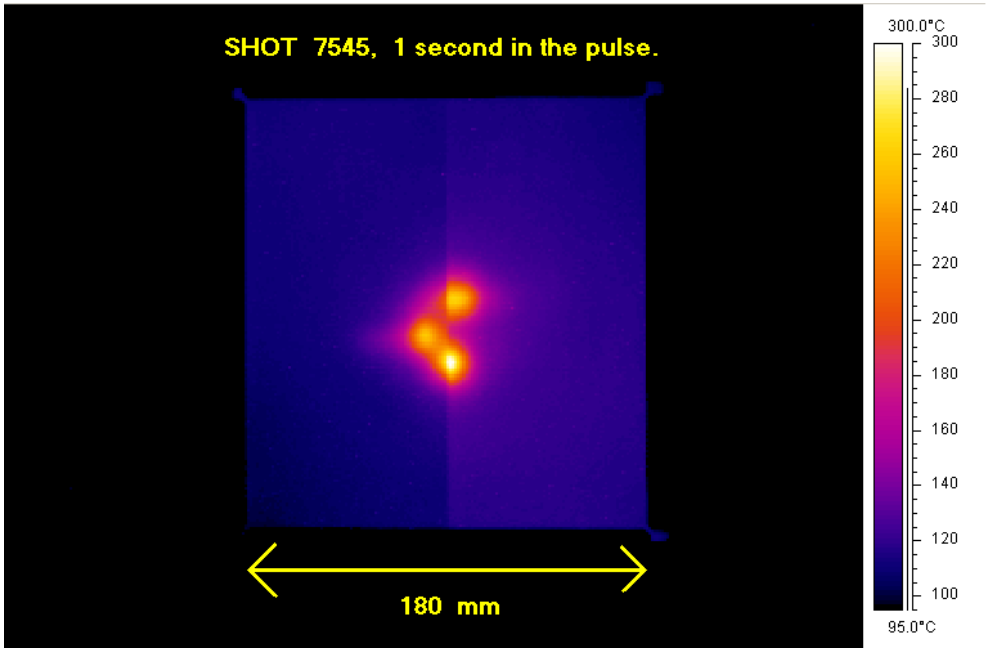
Accelerator and ion source during assembly

Results from SINGAP accelerators

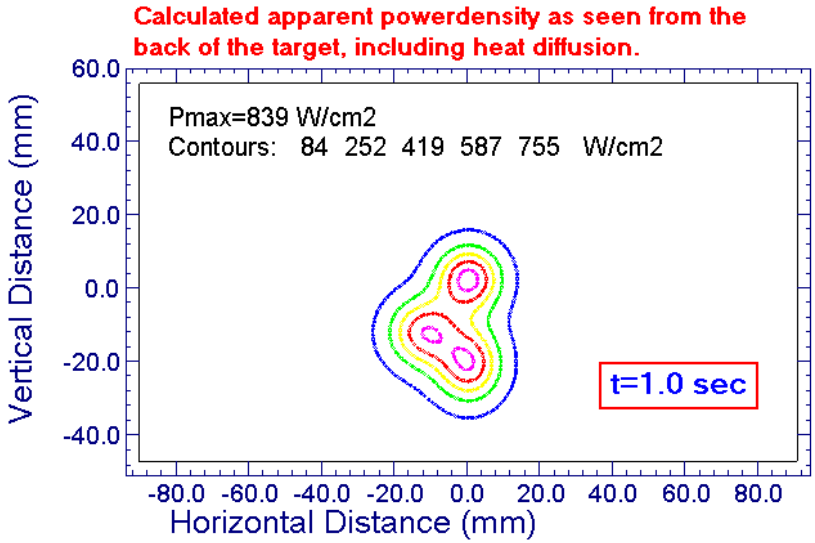
	Prototype accelerator 625 mm gap	Prototype accelerator 350 mm gap	"ITER-like" 350 mm gap
HV only gas added to suppress dark current	1000 kV 0,017 Pa Helium	940 kV 0.03 Pa Helium or Deuterium	940 kV 0.07 Pa Helium or deuterium
Deuterium beams	910 keV 3 mA/cm^2 600 keV 7 mA/cm^2	914 keV 5 mA/cm^2 500 keV 12 mA/cm^2	850 keV 1.5 mA/cm^2 730 keV 12 mA/cm^2 580 keV 15 mA/cm^2
Comments	Over focused beams	Over focused beams	Optics OK for ITER

Beam measurements

IR data from back of the 1D Mitsubishi MFC 1A graphite target.



IR picture taken after 1 s of beam with Flir 550 IR camera system

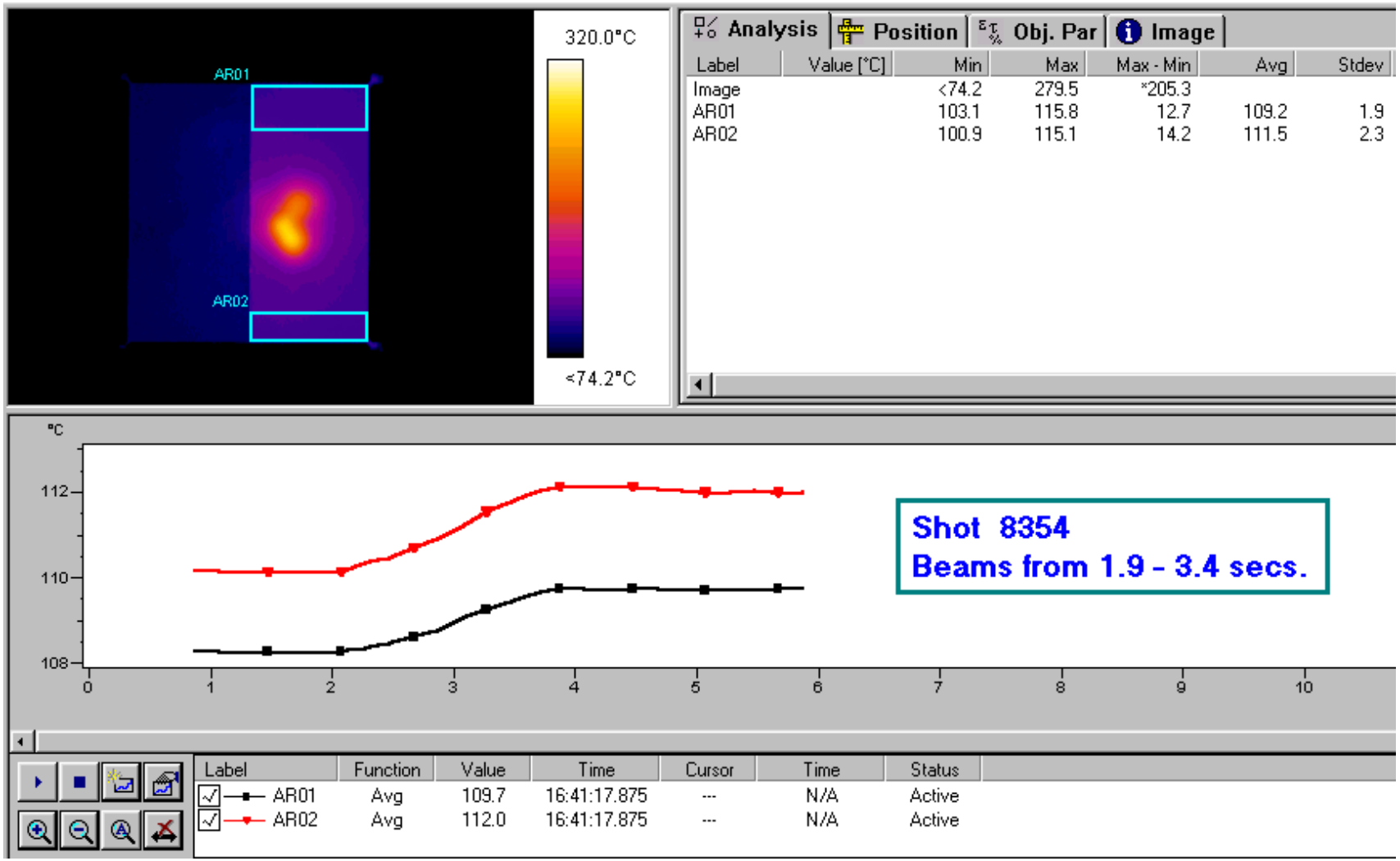


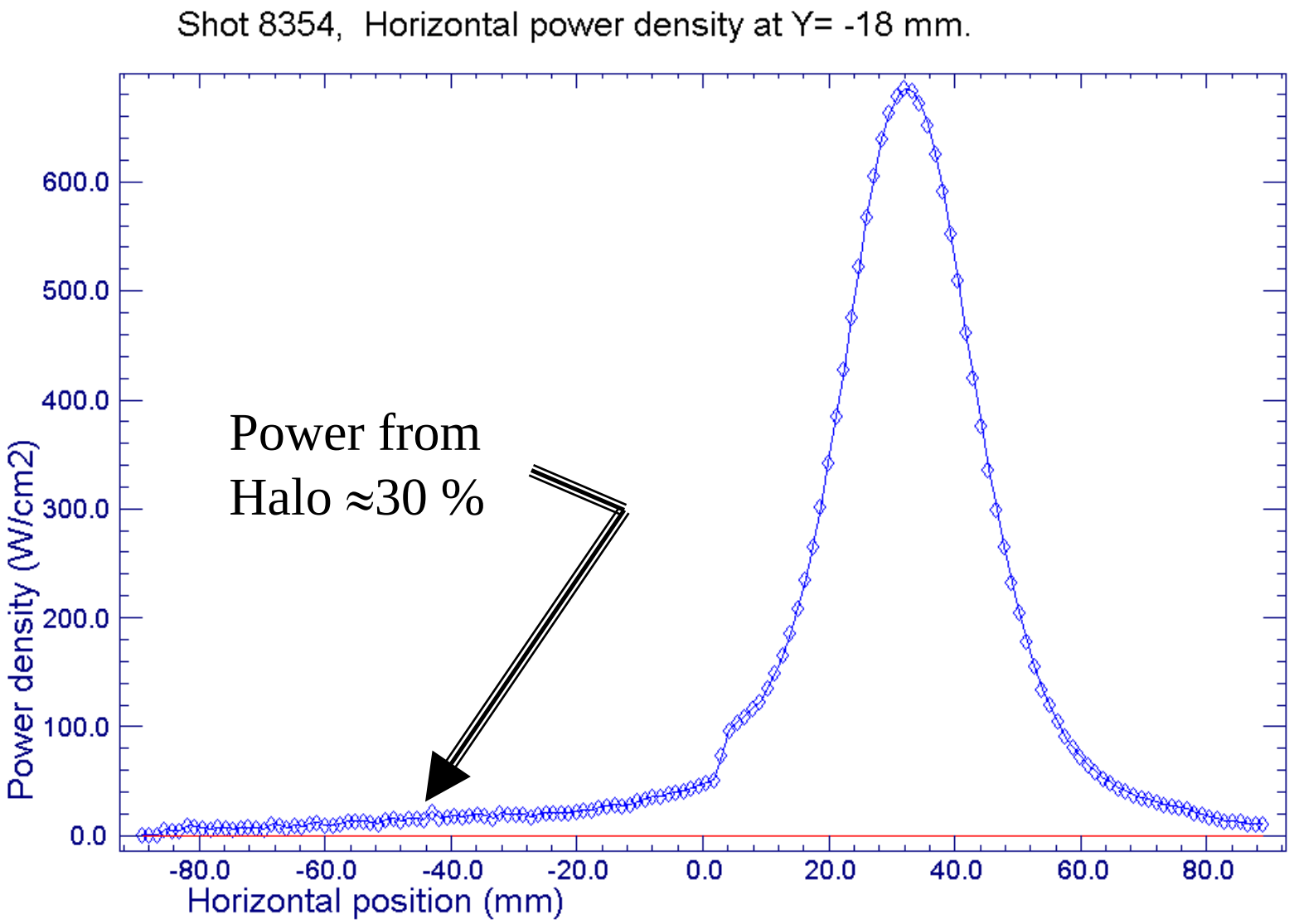
Power density profile 1 s after beam turned off, from data with Agema 782 IR camera system

For the shown shot (7545), the expected power density profile was calculated.

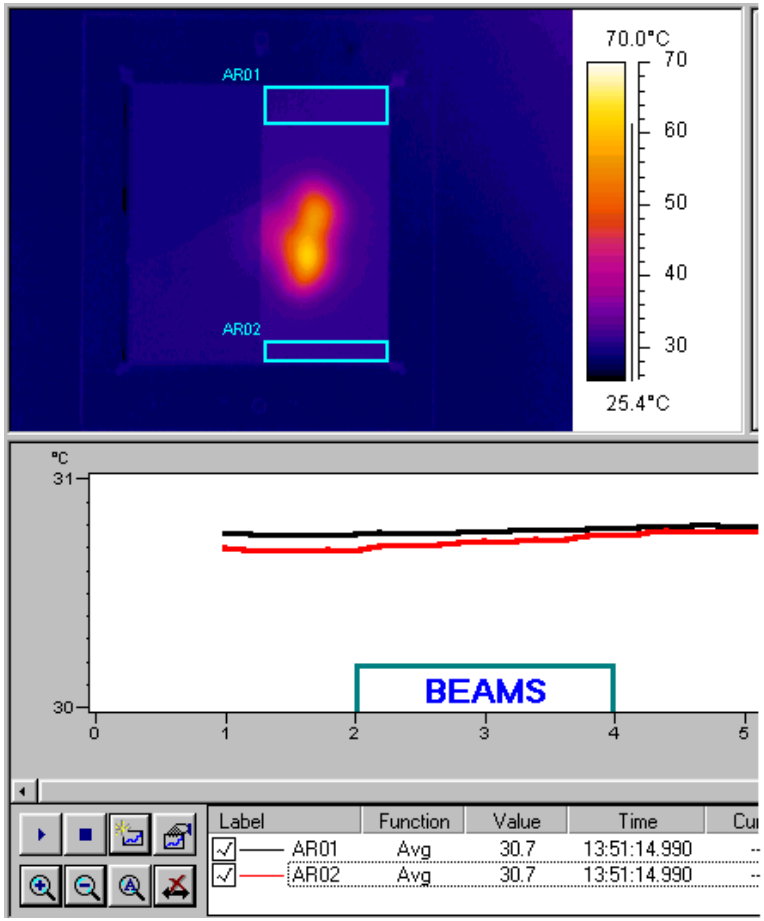
- Due to the magnets in the pre-accelerator, the aperture pattern is distorted. This is expected and included in the ITER design.
- The centre beamlet is 7 mm higher than calculated.
- The beamlet divergence is close to 3 mrad.
- The measured power density is too low.
- A halo seems to be present

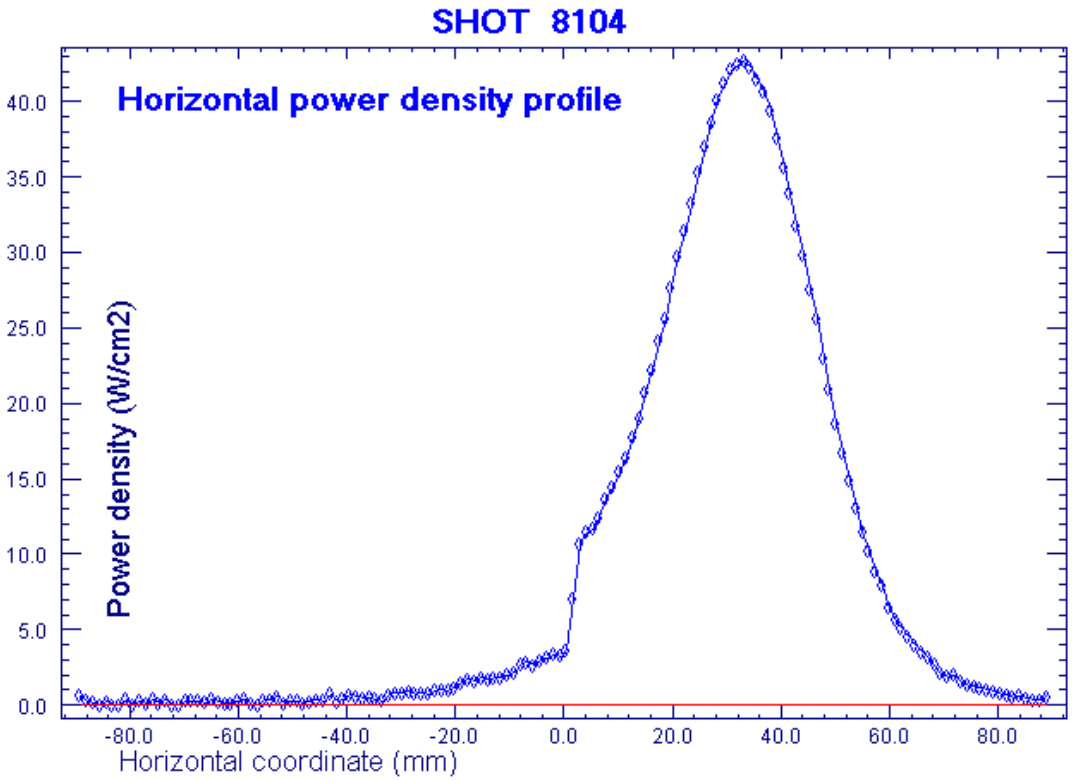
A Halo can be seen in shots with Cs !



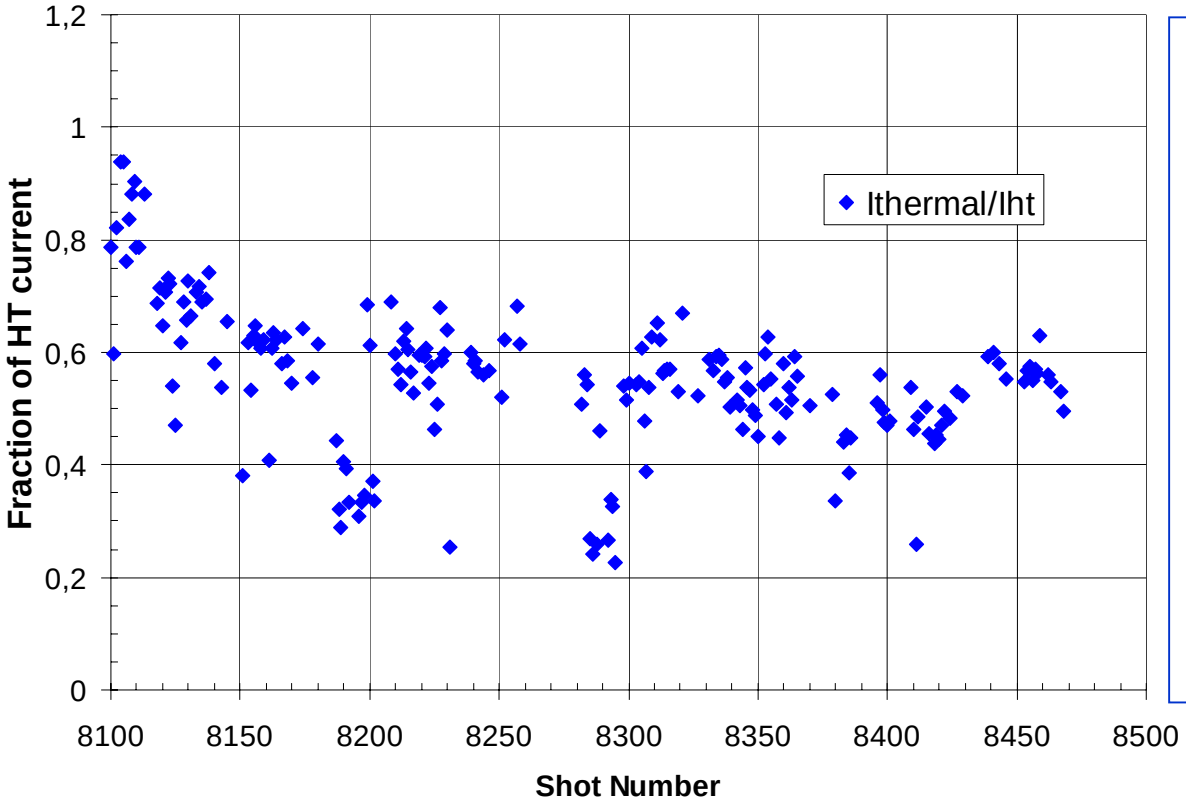

Shot 8354, Horizontal power density at Y= -18 mm.
Power from
Halo ≈30 %
Power density (W/cm2)
600.0
500.0
400.0
300.0
200.0
100.0
0.0
-80.0
-60.0
-40.0
-20.0
0.0
20.0
40.0
60.0
80.0
Horizontal position (mm)

No obvious Halo in volume production without Cs !





Transmission



Current needed from MV Power Supply:

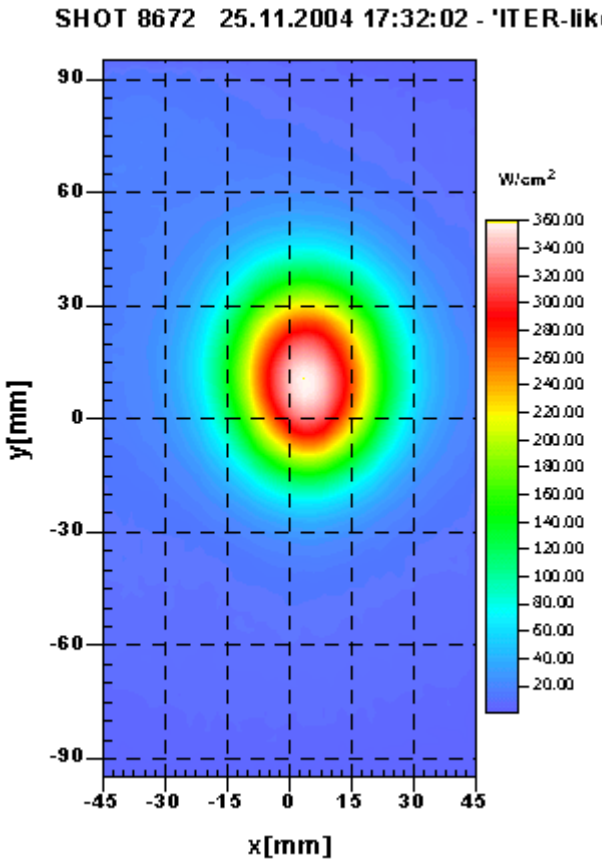
(3 apertures)x1.5 cm^2 x(J^- = 20 mA/cm^2) = 92 mA

With 60 % transmission we would need 153 mA to have 20 mA/cm^2

MV PS limit=100mA

- We measure ≤60% of the electrical current as power on the target.
- Therefore cannot reach objective with 3 apertures → **single** aperture.

ACCEPTABLE ITER-RELEVANT OPTICS



Shot 8672

V2 = 3.5 kV
V3 = 25.5 kV
V4 = 576 kV
J = 7.8 mA/cm2

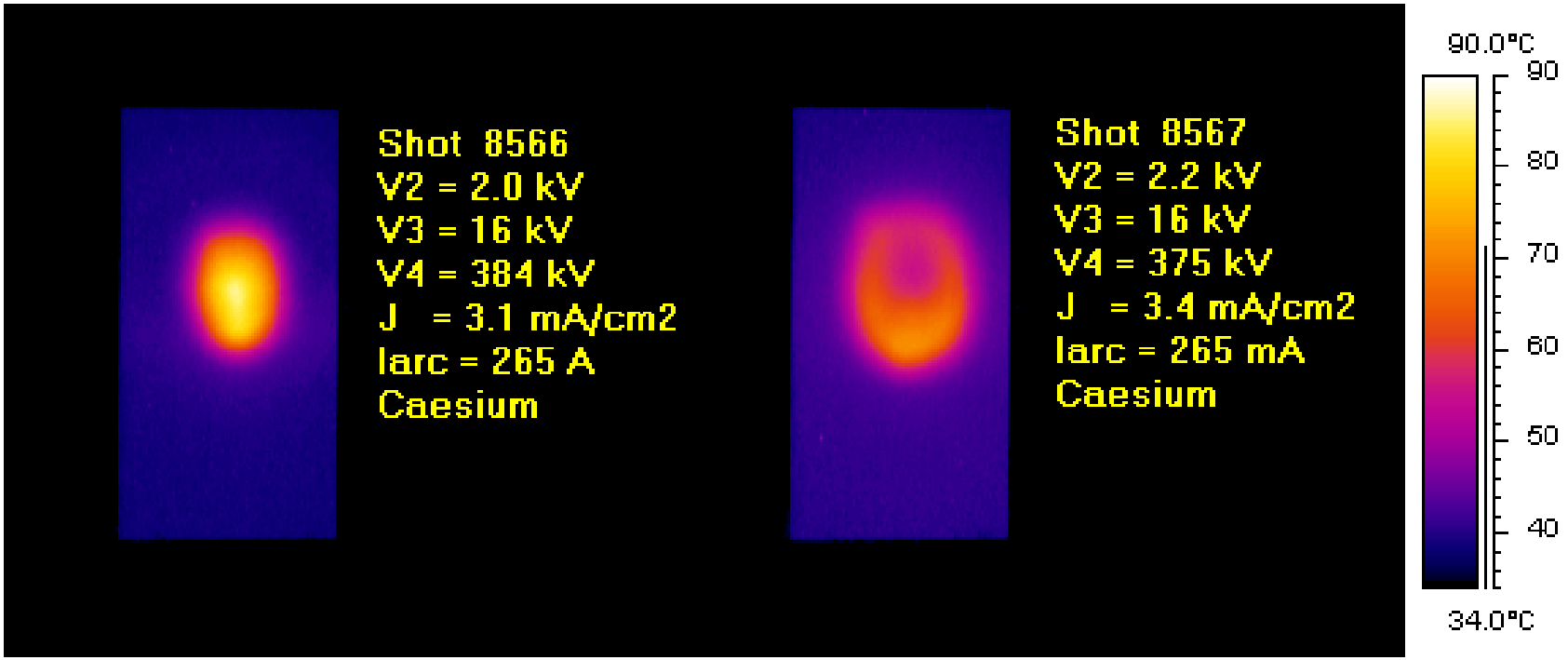
T = 1.0 sec
profile taken
2 sec after shot

Beamlet divergence for ITER-Relevant shot 8672.

Horizontal: **<5.3 mrad**
Vertical:**<6.8 mrad**

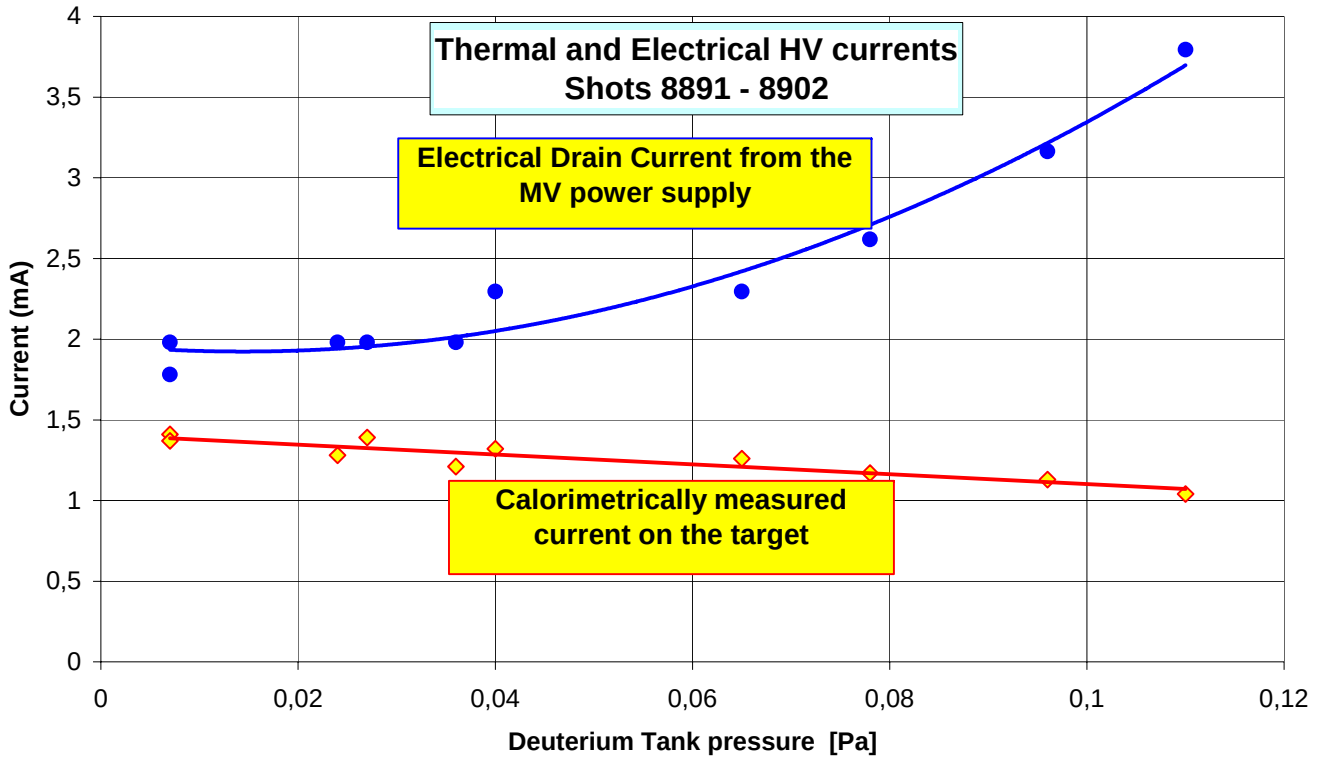
Lateral heat diffusion in target not taken into account.

SENSITIVE OPTICS



- **Two nearly identical shots in Caesium with very different beamlets.**
- **Often in an elliptical shape.**
- **Flipping states (plasma on/off knife edge)?**
- **Flipping can be triggered by V2, arc power and/or bias.**

TRANSMISSION DEPENDS ON TANK PRESSURE



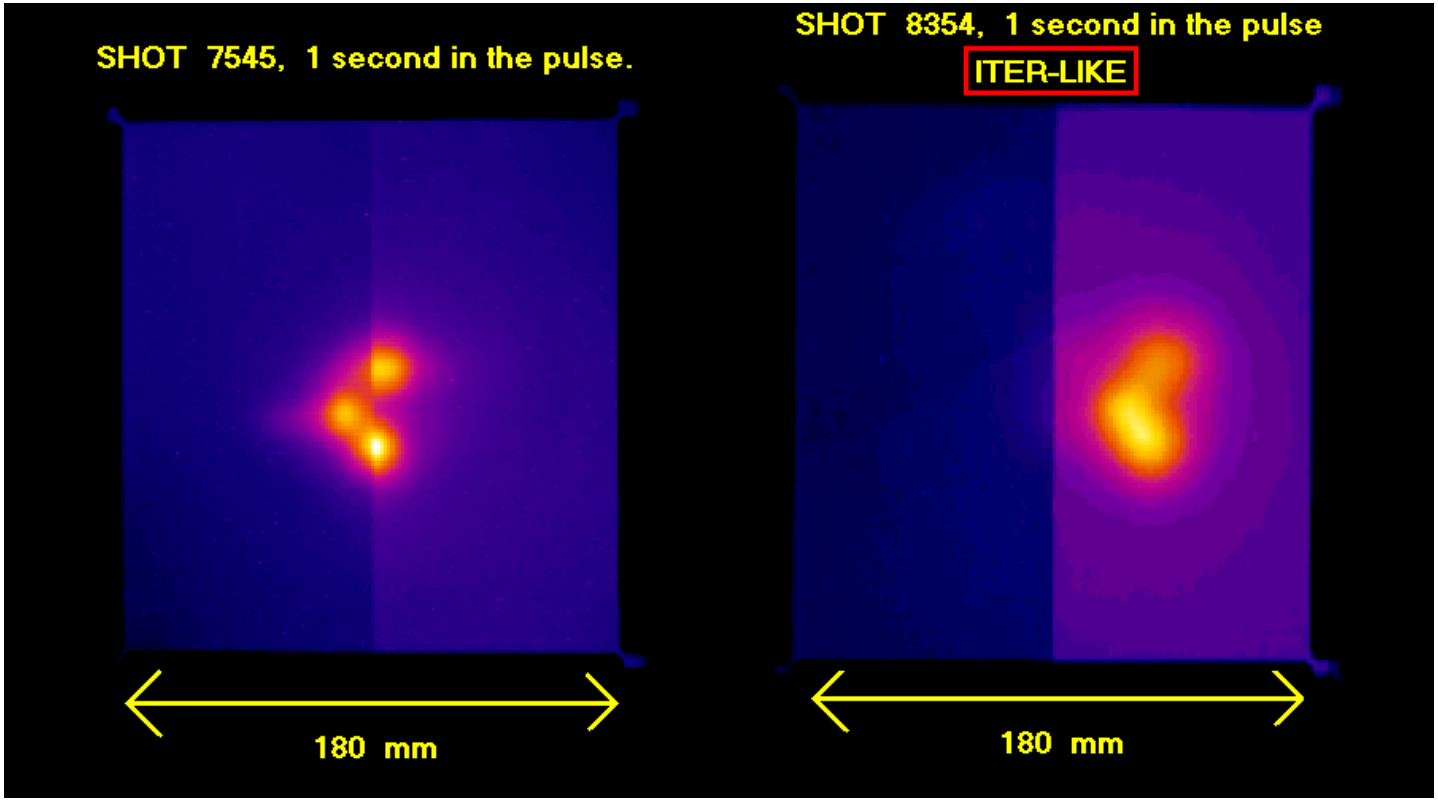
Due to stripping, the THERMAL current decreases with pressure.

The ELECTRICAL drain current increases with pressure.

The TRANSMISSION goes down sharply with pressure.

The halo is not effected by stripping losses.

Aperture Offset Steering Works !

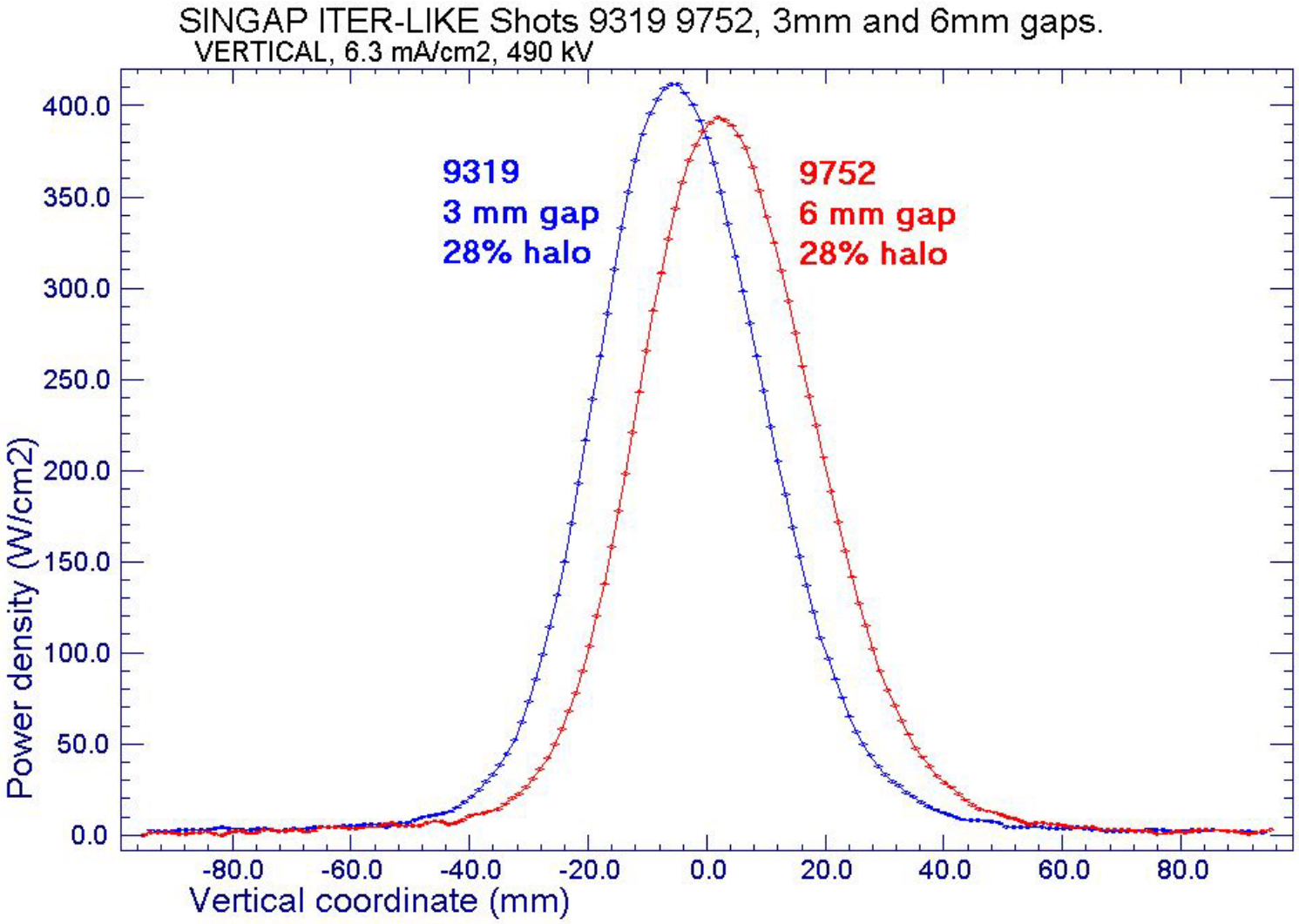


Displacing the anode aperture by -16 mm for a desired steering of +32 mm resulted in an actual steering of +32 mm (12 mrad). ITER needs ±10 mrad.

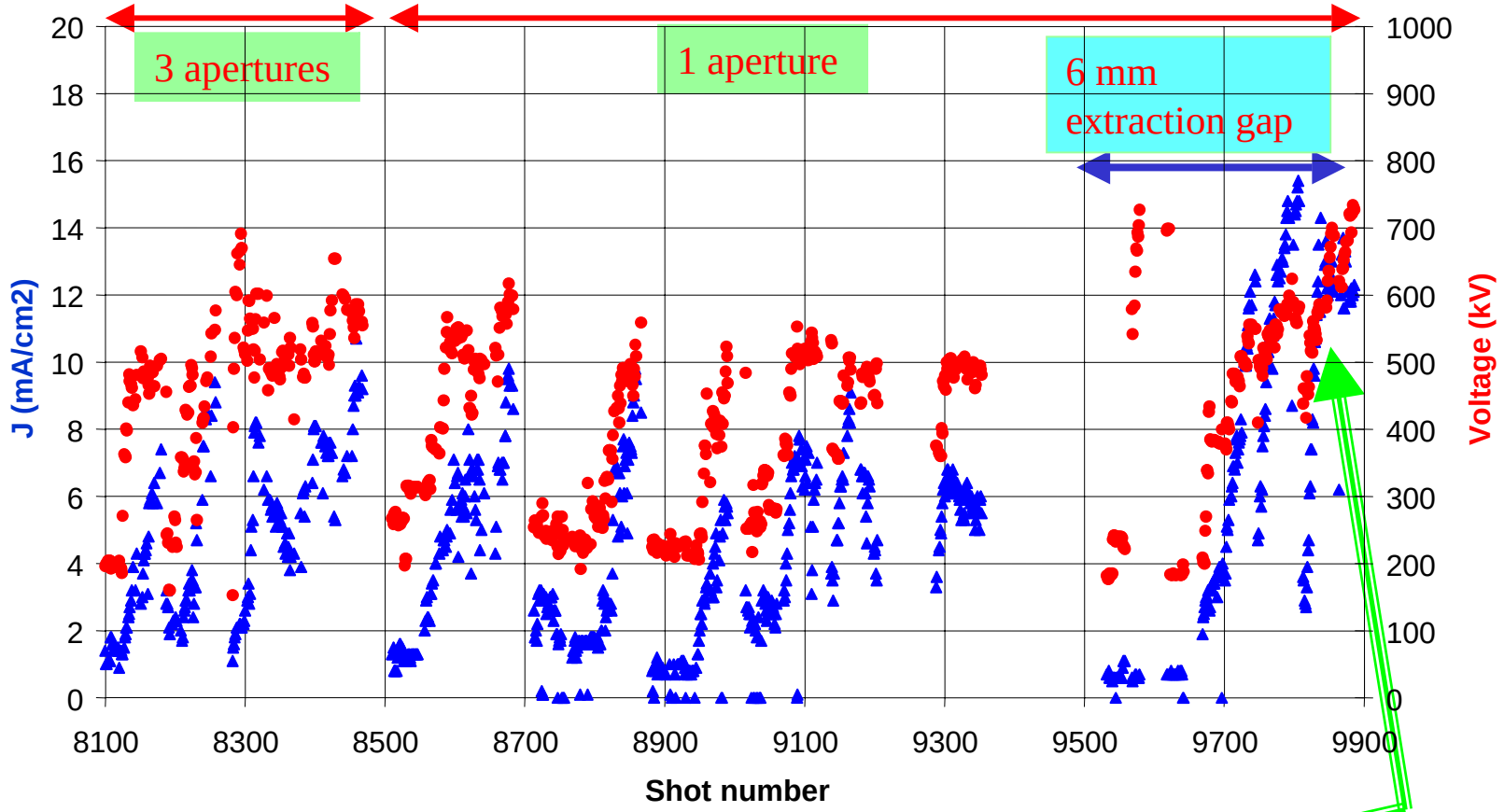
3 or 6 mm Extraction Gap ?

- 3 mm extraction gap was originally chosen to reduce power from the intercepted co-extracted electrons since the extraction voltage could be kept low .
- With the 3 mm extraction gap and a 14 mm diameter aperture the accelerator was **very sensitive** to small changes in extraction voltage, pre-acceleration voltage, bias or arc power.
- The pre accelerator was therefore re-gapped to give an extraction gap of **6 mm**. Pre-acceleration gap remained at 20 mm.

Vertical profiles for 3 and 6 mm extraction gap



Performance of all shots done with new IR camera



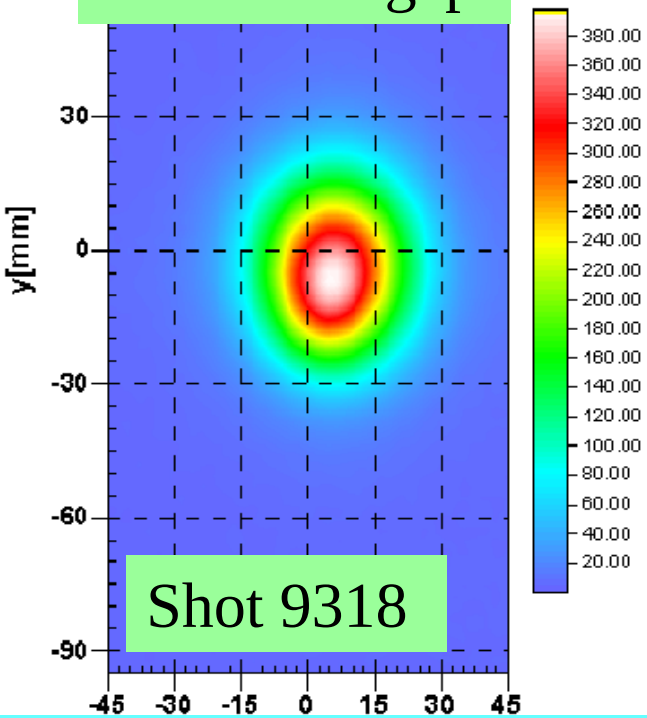
580 kV 15 mA/cm^2 and 730 kV 12 mA/cm^2 D$^-$ achieved with 6 mm extraction gap

Results from operation with 6 mm extraction gap

After only three days of operation with 6 mm gap:

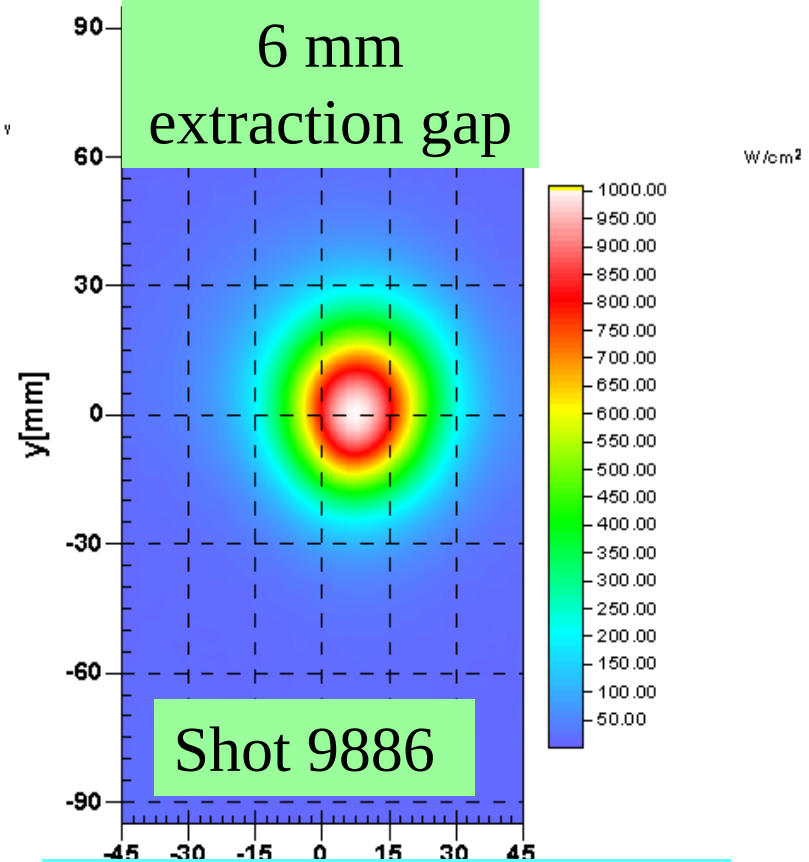
1. 50 % Higher current densities, 15 mA/cm^2, 580 keV D$^-$
2. Impossible to trigger a hollow beam
3. Less sensitive to small variations of voltages or arc power
4. 730 keV 12 mA/cm^2 D$^-$ beams ***with*** ITER-relevant optics.

3 mm extraction gap



496 keV, 6.4 mA/cm^2 D$^-$
Div$_{hor}$=3.6mrad
Div$_{ver}$=5.2 mrad
Halo =28 %

6 mm extraction gap



727 keV, 12 mA/cm^2 D$^-$
Div$_{hor}$=3.9 mrad
Div$_{ver}$=5.5mrad
Halo=31%

4. What's next ?

- Increase beam energy and current density to values as close as possible to 20 mA/cm^2 and 1 MeV. This might only be possible by solving the dark current problem.
- Install *5-aperture plasma grids* and measure the effects of the "kerbs".
- Carry out test of the reliability of a SINGAP accelerator. Attempts will be made to fire a sequence of 50-100 pulses of up to 2 s length onto the beam dump with an energies close to 1 MeV.
- When the above measurements have been done we plan to install the *"ITER-like" SINGAP accelerator at JAERI, Naka in Japan* for high current tests where a 1MV power supply with a current capability of 1 A is available. A direct comparison between the MAMuG and SINGAP accelerator could then be done.

5. Conclusions

- ☺ *HV shots with "ITER-like" accelerator can hold 930 kV without breakdowns.*
- ☺ *Reached:* *850 keV with 1.5 mA/cm^2 D$^-$ in volume*
  580 keV with 15 mA/cm^2 D$^-$, 6 mm extraction gap
  730 keV with 12 mA/cm^2 D$^-$, 6 mm extraction gap
- ☺ *Beam steering by moving the anode aperture works.*
- ☺ *Power accountability is good (90 %) in the absence of background gas. If gas is added power accountability drops sharply. Ionisation of the background gas ➔ backstreaming ions?*
- ☹ *A halo is present. It seems more pronounced in Cs than in volume.*
- ☹ *With 3 mm extraction gap the beam-optics can flip between "peaked" and "hollow" on minor changes to extraction voltage, plasma grid bias or arc parameters.*
- ☺ *A perveance scan near ITER-like optics gave a horizontal divergence of 3.6 mrad and a vertical divergence of 5.2 mrad. These divergences includes heat difusion inside the target.*

Acknowledgements

The presenter would like top thank JET Neutral Beam Testbed group for the loan of the FLIR 550 IR camera system.

These experiments would not have been possible to do without this camera.